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Modelling and surgical analysis of fracture repair of the facial skeleton using generic and patient matched finite element models

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This dissertation is submitted for the degree of Doctor of Philosophy

CERTIFICATE OF ORIGINAL AUTHORSHIP

This thesis is the result of a research candidature conducted jointly with another University as part of a collaborative Doctoral degree. I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Richard Conway **Date**

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Whilst this research thesis is novel, it draws from previous works to understand where finite element analysis began to where it is currently, as well as its limitations to date, particularly in the fields of medicine and dentistry. In particular, I have drawn extensively on the technical expertise of my academic colleagues so that I could provide my surgical expertise to produce this work. As such special acknowledgement goes to the following:

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Last but not least I would like to thank Lei Cameron who helped me in proofreading and formatting my thesis, as well as providing valuable insight into my preparation of this document.

PREFACE

As a surgeon working in the maxillofacial field I have always had a keen interest in trauma of the facial skeleton. As part of my contact at the University of Technology with Professor Ben-Nissan, Professor Milthorpe, Dr Choi and Dr Taraschi over the past 20 years I have had the honour of being involved in finite element based research. During this time, it became apparent that utilising this methodology to analyse both current fracture management and future directions of fracture management was a worthy ground for research as part of a doctorate of philosophy. To achieve this goal, I have been most fortunate to have the wealth of technical knowledge from my aforementioned university colleagues to draw upon and integrate into my surgical expertise.

The following dissertation presents my analysis as a surgeon of modelling and fracture repair of the facial skeleton, using generic and patient matched finite element models with technical support provided by those academic colleagues addressed in my acknowledgements.

I hope that those who read this thesis, whether scientists or clinicians or both, find it as interesting as I have.

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Appendix A

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PUBLICATIONS ARISING FROM RESEARCH WORK

A.H. Choi, B. Ben-Nissan, R.C. Conway, & I.J. Macha (2104). *Advances in calcium phosphate nanocoatings and nanocomposites*. Advances in Calcium Phosphate Biomaterials, Springer Publishing, pp. 485-511.

A.H. Choi, B. Ben-Nissan, & R.C. Conway (2014). Finite Element Analysis (FEA) in Dentistry. In *Handbook of Oral Biomaterials*, J.P. Matinlinna (Ed.), Singapore: Pan Stanford Publishing, Ch. 17, pp. 535-576.

A.H. Choi, B. Ben-Nissan, & R.C. Conway (2005). Three‐dimensional modelling and finite element analysis of the human mandible during clenching. *Australian Dental Journal*, *50*(1), 42-48.

A.H. Choi, J.P. Matinlinna, R.C. Conway, & B. Ben-Nissan (2012). Application of Biomaterials and Finite Element Analysis (FEA) in Nanomedicine and Nanodentistry. In: Computational Finite Element Methods in Nanotechnology, S.M. Musa (Ed.), CRC Press-Taylor and Francis Group, USA, Ch. 11, pp. 373-399.

A.H. Choi, R.C. Conway, & B. Ben-Nissan (2004). Finite element analysis of ceramic dental implants incorporated into the human mandible, *Key Engineering Materials*, *254*, 707-712.

A.H. Choi, R.C. Conway, V. Taraschi, & B. Ben-Nissan (2014). Biomechanics and functional distortion of the human mandible, *Journal of Investigative and Clinical Dentistry*, *6*(4), 241-251.

A.H. Choi, B. Ben-Nissan, J.P. Matinlinna, & R.C. Conway (2013). Current perspectives: Calcium phosphate nanocoatings and nanocomposite coatings in dentistry. *Journal of Dental Research*, *92*(10), 853-859.

ABSTRACT

Surgical analysis of fracture repair of the facial skeleton using generic and patient matched finite element models

This thesis is aimed at finite element modelling of the fractured and repaired facial skeleton, specifically the mandible and surgical aspects that influence a rapid and complete recovery process without complications that otherwise lead to significant patient morbidity and sometimes mortality.

The mandible, as a site of specific investigation, was chosen due to the following factors. Firstly, as a prominent part of the facial skeleton, the mandible is a highly complex structure, being composed in its hard tissue elements by cancellous and cortical bone and the dental complex consisting of enamel, dentine and cementum. These hard tissue components house the associated soft tissues consisting of major nerves and blood vessels, fat and other connective tissues. Already one can see the complexity of the mandible but its unique anatomical character does not stop there as the entire structure articulates with the remainder of the facial skeleton via the temporomandibular joints.

The mandible is also unique because it is being commonly affected by all of the major disease classifications, being congenital, traumatic, neoplastic, infective, inflammatory and iatrogenic disease. As a consequence, clinicians ranging from dentists through to maxillofacial surgeons are often confronted with complex disease patterns that require complex reconstructive methods to restore form and function (Figure 0.1). At the terminus of reconstruction, these elements of form (cosmesis) and function (speech, facial expression, mastication, deglutition, taste and airway maintenance) are what our patients demand and should be entitled to expect from modern day surgical techniques.

The aim of this work is to look at the fractured mandible using finite element modelling and ascertain what provides the surgeon with the best results when performing

osteosynthesis of the fracture and hence lead to rapid, complete and complication free healing.

The models used in this thesis are based on a well established and validated model, initially taking its heritage from the works of Ben-Nissan in 1987, followed by Choi in 2005. In this thesis, it is termed the 'generic (GEN) model'. A second model is also used throughout this thesis, which is based on computed tomography scans of a human mandible, termed as the 'patient specific (PS) model'. With the GEN and PS models, various fracture fixation systems were designed and applied to both FE models and analysed for their efficacy. This brings to the study a unique attribute of comparing a GEN model with a PS model, thus allowing multiple fracture fixation systems to be analysed. In doing so, a better correlation is provided with the pathophysiology and mechanics of trauma as it occurs in vivo.

The results of this study show that most importantly we have been able to produce a valid models that closely mirrors trauma and its repair as occurring in real life, not just as it appears in laboratory analysis.

Not only are the models valid, but equally important, they are predictably reproducible. Specifically, the PS model could be applied in PS scenarios to allow a customised design of surgery that best suits the individual in question.

In the analysis, we studied various plate shapes ranging from traditional linear plates to mesh pattern fixation plates. We also looked at various plate material ranging from titanium alloy (Ti-6Al-4V) to zirconia (ZrO_2) and polylactic acid (PLA) and also in various dimensions.

With the analysis of these variants we found that whilst there were variations in performance between the various designs, they all performed equal to the physical parameters required for fracture fixation and subsequent repair. Across all variants of fixation methods, one significant factor is that the fractured ends of the bone are applied as closely as possible but not compressed.

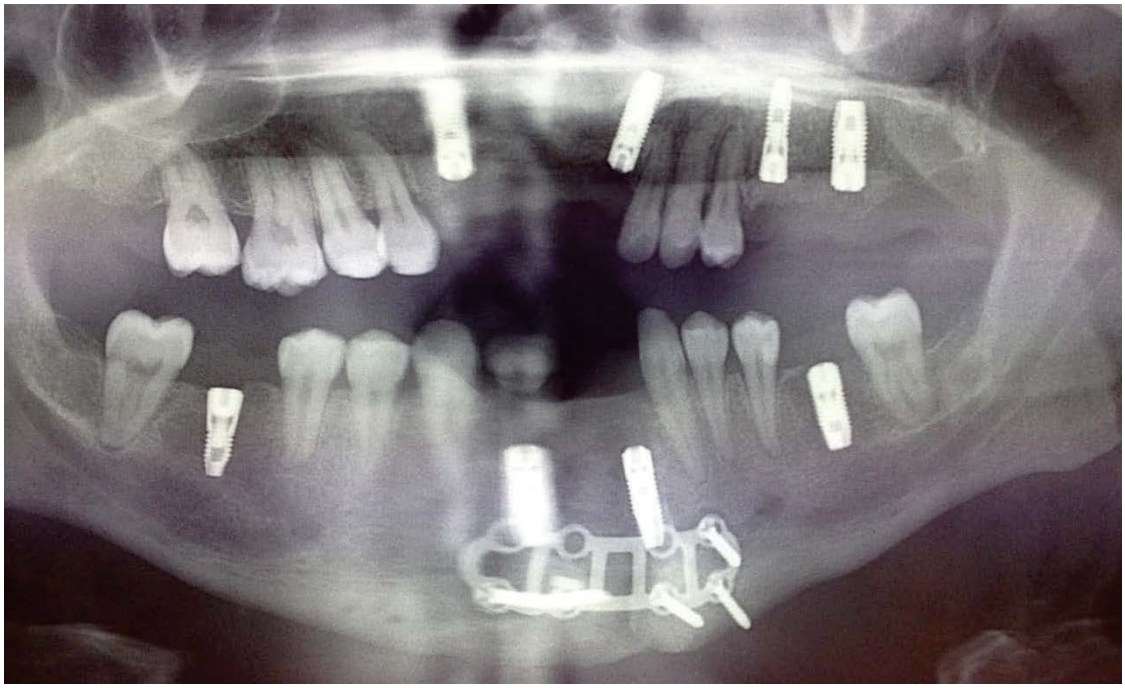

Figure 0.1 Facial skeleton affected by congenitally associated tooth absence and neoplasia, requiring complex reconstruction with dental implants, grafting and fixation plate

The final product of this work is a reproducible valid model where production, performance and results represent a dialectic improvement over past mandibular models and which reproduces the most realistic scenario of constraints and forces during functional movements.

With further improvements, such as patient specific bone mineral density and the use of dedicated software for the manipulation of the computed tomography data, this model is destined to become a functional tool for clinical diagnosis and treatment in maxillofacial surgery and dentistry.

ABBREVIATIONS

CBCT	cone beam computed tomography
CT	computed tomographic
EMG	electromyogram
FEA	finite element analysis
FEM	finite element model
FS	fracture segment
GEN	generic
IEMG	integrated electromyogram
IP	isolated plate
MRI	magnetic resonance image
PLA	polylactic acid
PS	patient specific
Ti	titanium
Ti-6Al-4V	titanium alloy
TMJ	temporomandibular joint
ZrO_2	zirconium oxide (also known as zirconia)